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Coordinating Multi-Site Construction Projects Using Federated Clouds

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Abstract

The requirements imposed by AEC (Architecture/ Engineering/ Construction) projects with regards to data storage and execution, on-demand data sharing and complexity on building simulations have led to utilising novel computing techniques. In detail, these requirements refer to storing the large amounts of data that the AEC industry generates – from building schematics to associated data derived from different contractors that are involved at various stages of the building lifecycle; or running simulations on building models (such as energy efficiency, environmental impact & occupancy simulations). Creating such a computing infrastructure to support operations deriving from various AEC projects can be challenging due to the complexity of workflows, distributed nature of the data and diversity of roles, profiles and location of the users.

Federated clouds have provided the means to create a distributed environment that can support multiple individuals and organisations to work collaboratively. In this study we present how multi-site construction projects can be coordinated by the use of federated clouds where the interacting parties are represented by AEC industry organisations. We show how coordination

can support (a) data sharing and interoperability using a multi-vendor Cloud environment and (b) process interoperability based on various stakeholders involved in the AEC project lifecycle. We develop a framework that facilitates project coordination with associated “issue status” implications and validate our outcome in a real construction project.

20 *Keywords:* , Coordination, AEC Projects, Collaboration, CometCloud,
21 Clouds

22 **1. Introduction**

23 In the Architecture/ Engineering/ Construction (AEC) industry, projects
24 are increasingly being undertaken by consortia of companies and individuals,
25 who work collaboratively for the duration of the project. Such projects are
26 complex and the consortia members provide a range of skills to the project
27 from its inception to completion. During this process, various data arti-
28 facts are also generated that need to be stored and shared between project
29 members (generally using access control strategies – which limit what can be
30 accessed at a particular stage of the AEC project lifecycle). The planning,
31 implementation and running of these AEC industry projects requires the for-
32 mation of secure Virtual Enterprises (VEs) to enable collaboration between
33 its members by sharing project information and resources. An important
34 feature of the consortia is that they are dynamic in nature and are formed
35 for the lifetime of the project [2]. Members can participate in several con-
36 sortia at the same time and can join or leave a consortium as the project
37 evolves. Cloud computing offers an important computing infrastructure to
38 facilitate the establishment and coordination of such VEs. Cloud comput-

ing is expected to enhance capabilities that were generally offered through services made available over the Internet. As well as remote access, Cloud computing also provides enhanced security infrastructure including single sign-on capability, security between consortia members, simple setting up of networks to support VEs, distribution of computationally intensive jobs across multiple distributed processors (based on shared information about available resources) [4]. Each organisation involved in a VE may have access to its own Cloud computing system (privately managed internally within the organisation, or acquired through a public provider such as Amazon.com or Microsoft (via their Azure platform)). As it is unlikely that all members of a consortium will share the same platform, integration across multiple platforms is therefore an essential requirement for such VEs to function in an efficient and reliable manner [1].

In the computer science research, various efforts have been proposed to implement such multi-Clouds with research efforts focusing on Cloud interoperability e.g. the Open Cloud Computing Interface (OCCI) efforts at the Open Grid Forum [6]. OCCI provides an API and a set of protocols to enable management capability to be carried out across multiple Cloud providers. A variety of implementations are currently available, in systems such as OpenStack and OpenNebula (two open source Cloud platforms). An alternative approach to interoperability is through the development of specialist gateway nodes which enable mapping between different Cloud systems and the implementation of specialist gateways to connect different Cloud systems, the development of a Cloud Operating System (CloudOS) to connect distributed Clouds (European FP7 “UNIFY” project) to the use of specialist in-network

64 capability to process data in network elements between different end points
65 (GENICloud [7]). Similarly, on-line sites such as CloudHarmony [8] report
66 over 100+ Cloud providers that offer capability ranging from storage and
67 computation to complete application containers that can be acquired at a
68 price, primarily using service-based access models.

69 On the other hand, in the AEC industry there is an increased interest in
70 Building Information Modelling adoption. Such modelling process for various
71 construction projects represents a complex task. This complexity comes from
72 the construction projects which often require collaboration between employ-
73 ers, designers, suppliers and facilities managers through a range of design and
74 construction tasks. Therefore, using cloud federation in a BIM context can
75 provide a number of benefits such as: (a) reduced project failure caused by
76 lack of effective project team integration across supply chains (b) emergence
77 of new challenging new forms of procurement i.e. Private Finance Initiative,
78 Public-Private Partnership and the design-build-operate and (c) decreasing
79 the whole life cost of a building through the adoption of BIM in facilities
80 management [3, 5].

81 In this paper, we present the implementation and use of a distributed
82 Cloud system, based on requirements of the AEC sector. The resulting
83 clouds for coordination(C4C) framework can support merging and federa-
84 tion of various models of an infrastructure project from multiple applica-
85 tions, clouds and/or actors using a secure and robust common interface. The
86 process is based on BIM (Building Information Modelling) and data stored
87 by each participant conforms to the IFC(Industry Foundation Classes) data
88 model. We elaborate on the concept of project information “Issue Status”

89 associated with a project in order to determine issuing party’s status with
90 responsibility/liability associated and considering the reliance on the data.
91 Our approach involves the implementation of a logical “shared” space that is
92 physically distributed across multiple sites involved in the federation. Such a
93 shared coordination space enables various project members to interact with
94 each other during the stages of a project. We compare our approach to gen-
95 eral cloud federation efforts, specifically adapted for the needs of the AEC
96 industry in Section 2. In Section 3 we present the CometCloud system and
97 how this system has been used to create the federated cloud framework,
98 followed by a description of the “Cloud4Coordination” (C4C) system and
99 the associated Application Programming Interface (API) that makes use of
100 CometCloud in Sections 4 and 5. In Section 6 we evaluate the C4C system
101 by devising a project trial based on a real construction project and provide
102 overall conclusions in Section 7.

103 **2. Related work**

104 In this section we explore several related studies in the fields of AEC
105 collaboration and cloud federation.

106 *2.1. Related AEC technologies*

107 In the AEC industry the concept of decentralised repositories facilitating
108 data storage across multiple servers represents an emerging topic. Such de-
109 centralised environments are currently enabled by specialised software such
110 as Revit Server [24] and Bentley System’s ProjectWise [23]. In these sys-
111 tems, data is spread between multiple servers (termed integration and caching
112 servers in the case of Bentley, and hosts and accelerators for Revit Server).

113 However, current implementations do not remove the barriers of centralised
114 repositories. This is due to the fact that despite both Revit and Bentley
115 allowing the distribution of BIM data across multiple servers, there still re-
116 mains one authoritative (or master) copy of the data, hosted at a central
117 server. This centralized approach leads to both availability/access, security
118 and liability concerns, as data is being hosted on the server operated by one
119 organisation.

120 In addition to these commercial offerings, the concept of data storage and
121 collaboration is also a topic of active research in the AEC sector. In their
122 work on SocialBIM, Das et al.[25] have developed a BIM framework that pri-
123 marily focuses on modelling the social interactions between stakeholders. The
124 key development is SocialBIM’s ability to allow users to contribute/download
125 partial BIM models that are then merged/split from a “master” model held
126 in the SocialBIM cloud system(s). While this ability to work with small
127 “fragments” of BIMs which are then federated is a key development, the fact
128 that the end result is still stored in a centralised way in a cloud system will
129 be of concern to many organisations. Other work in this area includes Munk-
130 ley et al.[27], who have developed technologies to synchronize data between
131 Revit Server and an external storage server, enabling external users to see a
132 read only copy of the Revit (central) model. While this is an interesting way
133 of allowing increased collaboration using Revit Server, it does not adequately
134 provide for the dynamic two way collaboration that is often required in an
135 AEC project i.e. the ability to incorporate the results of other discipline’s
136 work (i.e. the architect, mechanical or electrical engineers) as background
137 in your own work. Finally, this approach is further limited as it is only able

138 to utilise the Revit proprietary data format. Additionally, Boeykens et al.
139 [28] have developed a layered client/server approach that provides an event
140 based communications pool between components embedded into BIM au-
141 thoring packages. This novel communication approach enables the dynamic
142 sharing of data between components. However, all data is still stored on a
143 centralised server that listens to the event based communications and both
144 saves and injects BIM data into the communications pool as needed. Other
145 solutions for supporting construction BIM data sharing and interoperability
146 include IFC ontology and IFC linked data with federated queries [12], seman-
147 tic linking and semantic web paradigms with orthogonal solution vector [13]
148 and views modelling [14] where companies work on the same model but with
149 individual access and views. The key differentiating factor of our work is
150 the distributed nature of our approach, where the authoritative copy of data
151 is always stored within a discipline’s own servers and is only federated with
152 other disciplines when required. Another key differentiating factor is the in-
153 creased level of dynamic communication that is possible between multiple
154 disciplines using our approach, i.e. when a single discipline makes updates
155 that are visible to other disciplines. These updates are automatically propa-
156 gated to the relevant disciplines, without a need for the other disciplines to
157 query if any updates have been made.

158 Many of these seemingly decentralised approaches (at least from a user’s
159 perspective), actually make use of centralised storage and coordination in-
160 frastructure. This is undertaken to ensure that the centralised system is
161 adequately protected and managed, and can be monitored for any discrep-
162 ancies or performance bottlenecks. Existing cloud-based deployments are no

different – as they make use of a single, centralised data centre. Our approach differs from these, in that we recognize that each institution involved in an AEC project will need to provide their own computing infrastructure, and more importantly will need to integrate their in-house capability with data centre based cloud systems that may be operated by other institutions/companies. Our approach therefore makes use of a Peer-2-Peer based approach, whereby local data centres can be aggregated with those of other institutions in a seamless manner, but still provide a centralised view on the data shared by institutions involved in a single AEC project. This is achieved using the CometCloud system as described in Section 2.2.

2.2. Related cloud federated systems

Through the federation of cloud systems it has become possible to connect local infrastructure providers to a common framework where participants can exchange data and collaborate. The mechanisms used to support cloud federation can bring substantial benefits for service providers by offering facilities for accessing global services instead of increasing costs associated with building new infrastructure (which may not be fully utilized and may only be needed to support peaks in workload over short time frames). A federated cloud also enables users to host applications with their cloud provider of choice – thereby making local decisions about pricing, software libraries/systems and deployment environments, while still being able to connect to other computational resources [30, 29, 32]. Various cloud bridging solutions are now available, such as IBM’s Cast Iron Cloud Integration [10], part of the Web Sphere suite of tools for developing and deploying applications across different environments. Cast Iron enables integration, through plug-ins, with

188 a number of IBM products (such as DB2) and systems from other vendors,
189 such as SAP and Salesforces CRM – thereby enabling integration between
190 in-house systems and public and private Cloud environments [17]. Many such
191 systems remain proprietary to particular vendors however and are hard to
192 customise to particular use scenarios. CometCloud [18] is an open source so-
193 lution that has been validated in a number of scientific and financial scenarios.
194 CometCloud has been demonstrated to work alongside specialist computing
195 environments (such as large scale computing clusters that are part of the US
196 TeraGrid and XSEDE projects) and public Cloud systems from Amazon (as
197 described below) [16].

198 A federated system may have a number of associated access and manage-
199 ment policies (based on the sites involved) to be considered in order to in-
200 crease the utility of providers contributing resources. CometCloud supports
201 a number of different federation models: (i) sites interact with each other
202 using direct communication and (ii) sites interact with each other using a
203 distributed coordination space [19]. In the C4C project, we use and extend
204 the second of these models to enable greater autonomy to be supported for
205 each site involved.

206 **3. Federation in a BIM context**

207 Collaboration in construction projects can bring together various partic-
208 ipating companies over the (building construction) lifecycle using different
209 systems and storage solutions. As part of this, the compatibility, control and
210 access of data objects created is critical to the success of a project. Currently,
211 coordination between participants is often a labour intensive manual process

and can require a monopoly of software systems to be enforced. A construction project is a complex undertaking depending on a large number of very different professions and firms [22, 37]. These firms range from SMEs to large multinational corporations. Each one of these organisation will participate in the construction project for a varying time period and, in that time period, will contribute different quantities and types of data to the project, or even contribute no data. As we have previously described, while interest in cloud based BIM solutions is increasing, there are still many obstacles to BIM adoption that must be overcome. These include: (a) lack of clarity as to who owns and is responsible for BIM (b) fragmentation of BIM data across design and engineering teams and then the contractor and FM companies and (c) information is not sustained across the lifecycle and is in continuous danger of being lost due to company mergers or bankruptcy [11, 15]. In response to these obstacles we propose the use of an BIM federation overlay to implement a federated distributed BIM data model within a construction project.

3.1. *CometCloud Federation*

Through the federation of Cloud systems it has become possible to connect local infrastructure providers to a global marketplace where participants can transact (buy and sell) capacity on demand. The mechanisms used to support cloud federation can bring substantial benefits for service providers by offering facilities for accessing global services instead of increasing costs associated with building new infrastructure (which may not be fully utilized and may only be needed to support peaks in workload over short time frames). More importantly, organisations with spare capacity in the data centre are

237 now provided with a simple way to monetize that capacity by submitting it
238 to the marketplace for other providers to buy, creating an additional source
239 of revenue.

240 The federation model is based on the Comet coordination “spaces” (an
241 abstraction, based on the availability of a distributed shared memory that
242 all users and providers can access and observe, enabling information sharing
243 by publishing requests/offers to/for information to this shared memory). In
244 particular, we have decided to use two kinds of spaces in the federation. First,
245 we have a single federated management space used to create the actual feder-
246 ation and orchestrate the different resources. This space is used to exchange
247 any operational messages for discovering resources, announcing changes at
248 a site, routing users’ request to the appropriate site(s), or initiating negoti-
249 ations to create ad-hoc execution spaces. On the other hand, we can have
250 multiple shared execution spaces that are created on-demand to satisfy com-
251 puting needs of the users. Execution spaces can be created in the context
252 of a single site to provision local resources or to support a *cloudburst* (i.e.
253 when additional capacity is needed to respond to a sudden peak in demand)
254 to public clouds or external high performance computing systems. Moreover,
255 they can be used to create a private sub-federation across several sites. This
256 case can be useful when several sites have some common interest and they
257 decide to jointly target certain types of tasks as a specialized community.

258 As shown in Figure 1, each shared execution space is controlled by an
259 agent that initiates the creation of such a space and subsequently coordinates
260 access to resources for the execution of a particular set of tasks. Agents
261 can act as a master node within the space to manage task execution, or

270 they have to interact through a proxy (P) and a request handler (R) to be
271 able to retrieve task information from the space and execute these..

272 3.2. *CometSpace*

273 CometCloud uses a Linda-like tuple space [31] referred to as “CometSpace”
274 which is implemented using a Peer-2-Peer overlay network. A tuple space
275 enables the implementation of an associative memory-based search strategy,
276 whereby the search term is described as a set of items/terms, which can be
277 mapped against a table of stored data. This search strategy is often easier
278 to implement in hardware and therefore provides a significant improvement
279 in search performance. As an illustrative example, consider that there are a
280 group of data producers and consumers, producers post their data as tuples
281 in the space, and consumers then retrieve data that match a certain pattern.
282 The producers/consumers only have a reference to where such data items
283 should be posted/retrieved from, but do not need to know the physical lo-
284 cation/ storage device for such data items. CometSpace [33] is an extension
285 to this tuple space-based abstraction, in that the tuple space can be phys-
286 ically distributed across multiple sites (data centres), and a “logical” space
287 is produced by combining these physically distributed sites. Each producer/
288 consumer now accesses the logical space, asynchronously, and does not need
289 to know the physical location of the site actually hosting the data. For our
290 needs we have updated the tuple-space mechanisms and the format of tuples
291 to comply with requirements related to data processing, data sharing and
292 data storage as identified in the construction sector. Therefore, a tuple be-
293 comes an array formed of {tuple-id, discipline-id, object-serialised, event-id}.
294 In this way, a virtual shared space for storing data can be implemented by

295 aggregating the capability of a number of distributed storage and compute
296 resources [20]. CometCloud therefore provides a scalable backend deploy-
297 ment platform that can combine resources across a number of different cloud
298 providers dynamically, often seen as a key requirement for a project in the
299 AEC sector.

300 CometCloud is based on a decentralized coordination substrate, and sup-
301 ports highly heterogeneous and dynamic cloud infrastructures, integration of
302 public/private clouds and cloudbursts. The coordination substrate (based
303 on a distributed Linda-based model) is also used to support a decentralized
304 and scalable task space that coordinates the scheduling of tasks, submitted
305 by a dynamic set of users, onto sets of dynamically provisioned workers on
306 available private and/or public cloud resources based on their Quality of Ser-
307 vice (QoS) constraints such as cost or performance. These QoS constraints
308 along with policies, performance history and the state of resources are used
309 to determine the appropriate size and mix of the public and private clouds
310 that should be allocated to a specific application request [18].

311 4. C4C project

312 In this section we outline the key industry-based requirements of the
313 “Clouds-for-Coordination” (C4C) project. We subsequently describe the
314 CometCloud-based system that has been implemented to address these re-
315 quirements.

316 4.1. Project background

317 The C4C project is addressed to the AEC industry seeking to facilitate
318 collaboration between organisations and looking at aspects related to BIM

319 data management and sharing. As BIM presents the possibility of sharing
320 information throughout the construction and property management sectors,
321 the problem of trust in the data becomes important – more commonly recog-
322 nised in the AEC industry through the use of ‘Issue Status’ for physical
323 documents (where documents are given statuses that equate to what they
324 can be reliably used for, and therefore what the issuing party accepts respon-
325 sibility and/or liability for). There are regulations in the UK, driven by the
326 government, to achieve fully collaborative Building Information Modelling
327 (BIM) (with all project and asset information, documentation and data be-
328 ing electronic) across the AEC sector [35]. This is an especially challenging
329 proposition as the successful delivery of a construction project is a highly
330 complex process; requiring collaboration between designers, suppliers and
331 facilities managers through a range of design and construction tasks. This
332 complexity in itself is a key motivation for the use of BIM, with anticipated
333 financial and time savings offered by its adoption [36]. Other motivating fac-
334 tors for BIM adoption include: (a) project failure caused by lack of effective
335 project team integration across supply chains [37, 22], (b) emergence of new
336 challenging new forms of procurement i.e. Private Finance Initiative, Public-
337 Private Partnership and the design-build-operate [38, 39], and (c) decreasing
338 the whole life cost of a building through the adoption of BIM in facilities
339 management[40].

340 The C4C project addresses the issue of BIM “ownership” by adopting
341 the approach that each party involved creates and stores (and is responsible
342 for) their own BIM information, rather than uploading it to a central server.
343 More specifically our architecture imposes the following key aspects: (i) the

ownership of data remains with the discipline that created that data – which also delegates any updates needed on the data to the discipline ensuring that there is a consistent view also maintained by the discipline owner; (ii) the use of a coordination layer to allow other users to transparently view data and make modification to it; (iii) enable information to be replicated across multiple disciplines (but remain consistent with the data owner), allowing for fault tolerance and prevent data loss. Another important aspect of a management model for BIM data is understanding the data and the stages (workflow) of an AEC project, in the context of how a BIM model is populated with data. In order to do this an abstract process has been defined as the result of our requirements gathering exercise. This process has abstracted the approaches defined in BS1192a[34].

In our coordination system we map each site to be a discipline, that can store BIM data, and can be hosted at different organisations that are part of a project. With the use of CometCloud system we deploy a working instance at each discipline by allowing a complete BIM dataset to be visualised, sourced from the information stored at multiple locations (locally managed Cloud systems), without changing how or where the original source material is kept, and ensuring that the capability of the owner to revoke and manage updates is not affected. The project goal is to create a framework for AEC project information “Issue Status”, which recognises both the issuing party’s status (and consequentially the responsibility/liability associated), as well as acknowledging the receiving party’s need or reliance on the data.

367 4.2. *Project implementation*

368 In the C4C project we consider that each site is a organisation involved
369 in a particular project can have one master (agent) and several workers.
370 We have also considered the scenario where a new site may be added dur-
371 ing the lifetime of the project, for instance, when a project member may
372 gain access to additional data centres. For addressing these requirements
373 we have developed a multi-cloud API which provides all the necessary op-
374 erations for managing collaboration once an AEC project has been initiated
375 and launched.

376 We implement a multi-cloud API for creating publishers, subscribers and
377 exchanging messages within our CometCloud-based system. The key benefit
378 of the publisher-subscriber model enables us to associate a distinct discipline
379 reference with each data producer. A user belonging to a particular discipline
380 (e.g. architect, electrical engineer, mechanical engineer etc) is able to have
381 limited visibility of BIM objects across the different sites that are part of a
382 particular project. What is visible within a specific discipline is dependent
383 on: (i) the current stage at which particular data has been produced; (ii)
384 the maturity of the generated object – referenced through a “suitability”
385 level. Both of these parameters are AEC industry specific requirements, and
386 ensure that objects can be managed and updated without conflict during the
387 lifetime of the project.

388 In our implementation we consider that each object has a named owner/discipline,
389 a last modified date and a (BS1192:2007+A1:2015) suitability code. These
390 attributes are associated individually at the time of a model upload. The
391 Suitability codes are defined in “BS1192:2007+A1:20015” and fulfil two roles:

392 (a) it is a claim or assertion made by the authoring organisation in the
 393 project, and (b) it is a licence or permission to those other roles to use the
 394 information as background to their work, up to the specified extent. We
 395 use [discipline-suitability] pairs to specify what suitability is attached to a
 396 discipline ([Discipline X - Suitability Y]). We also use suitability codes to
 397 determine when a discipline has visibility over other disciplines based on a
 398 suitability matrix. We consider that suitability can be applied to each ob-
 399 ject (per-object basis) and only objects that have a GUID i.e. inherit from
 400 IFCRoot can have a suitability. A differentiation case is at the upload stage
 401 when for convenience we specify suitability for all objects in the model to
 402 upload.

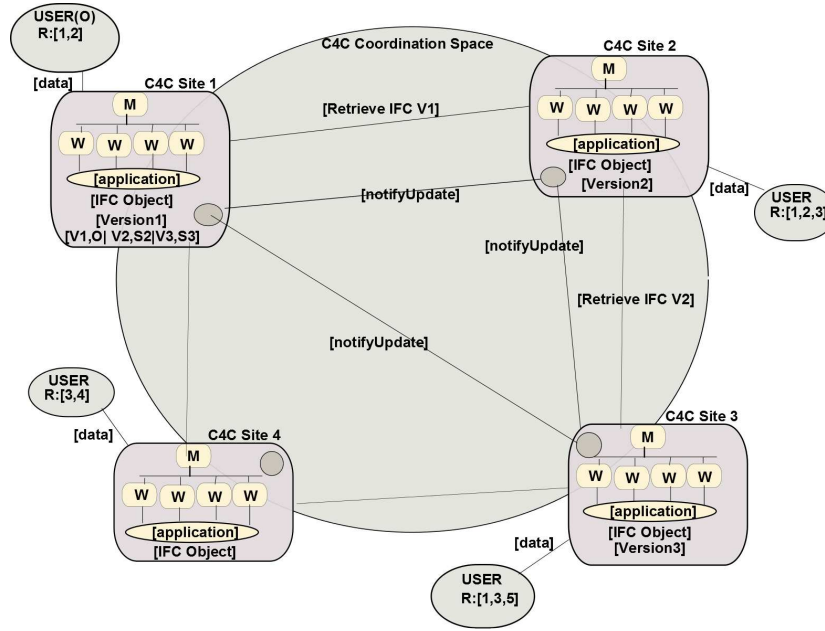


Figure 2: Clouds for coordination multi-site framework.

403 By using the publisher-subscriber model we enable sites to interact with

404 each other on a common project, using publishers to generate project tasks
405 and subscribers to execute these tasks. We consider the following properties
406 for a site:

- 407 • Industry Foundation Class (IFC) objects: a generic language and data
408 model for each of the sites in the coordination space. In our C4C model
409 we operate with IFC objects.
- 410 • Roles/Disciplines: we consider that sites can have different roles/ dis-
411 ciplines – which are considered when propagating notification messages
412 associated with updates to particular IFC objects, i.e. which site should
413 be involved at project collaboration stage.

414 Each site must support a local C4C environment, which enables other
415 sites to interact with it. In the workflow presented in Figure 2 and Figure 5,
416 Site 1 creates the C4C project which is formed of IFC objects locally stored
417 as *Version1*. All other sites participating in the project (Site 2 and Site 3)
418 will be notified about the new project being created (based on their roles in
419 the project). Based on the notification, Site 2 retrieves and updates the C4C
420 project with *Version1*, Site 2 then creates a new version of the C4C project
421 as *Version2*. When a new version is created the interested sites are again no-
422 tified. Site 3 will also retrieve the latest version *Version2* and apply updates
423 as part of a new project version – *Version3*. Another round of notifications
424 will be propagated to interested sites (Site 1 and Site 2). Site 4, although
425 part of the coordination space, is expected to contribute to the project at
426 later stages thus will not receive a notification event. It is important to note
427 that Site 1 is the owner of the project, along with the organisation that cre-

428 ates the project and can always retrieve the latest version of the C4C project.
429 In addition, Site 1 also keeps a list of the changes that have been applied
430 to the C4C project over time in a “provenance” (metadata) file. In our ex-
431 ample, Site 1, Site 2, Site 3 and Site 4 have associated suitabilities based
432 on which they can access the model and have visibility over other disciplines
433 (can access the objects updated/created by that discipline).

434 *4.3. Computing infrastructure*

435 Our coordination framework can be deployed on infrastructure with vary-
436 ing capabilities, ranging from regular servers to a cluster infrastructure. To
437 conduct our test deployments of the C4C system, we utilised IBM Softlayer ¹
438 virtualized cluster-based infrastructure hosted at IBM’s Amsterdam Data
439 Centre, utilising dedicated virtual servers. We utilised a total of four sets of
440 virtualised servers to simulate a construction project with four different dis-
441 ciplines. These are virtual servers hosted in different physical local locations
442 within Softlayer (simulating organisations with standard IT infrastructure
443 and also simulating organisations utilising a cloud based data storage infras-
444 tructure), allowing us to simulate a life-like scenario where disciplines within
445 a construction project will utilise multiple IT systems, hosted in differing lo-
446 cations. In the evaluation, we use a server specification of 16CPU cores with
447 64GB of memory. The networking infrastructure is 1Gbps Ethernet with a
448 latency of 14 ms on average. Each server runs Ubuntu 12.4 and Java 7.

¹<https://control.softlayer.com/> Last accessed: Aug 2015

449 5. C4C Application Programming Interface (API)

450 We adapt the functionality of CometCloud for the needs of interoperabil-
451 ity in construction projects. In this respect, we implement two APIs; one
452 for supporting multi-cloud use based on the publisher-subscriber (master-
453 worker) model (please refer to Table 1) and a BIM API to comply with the
454 industry standards as presented in Figure 3. The core methods in this API
455 are *getCurrentModel()* and *updateModel()*: where (i) *getCurrentModel()*
456 fetches the latest version of the model based on suitabilities and disciplines
457 visibility, and (ii) *updateModel()* pushes the model with associated changes
458 into the C4C system. For facilitating disciplines to use the background of a
459 project we have developed methods for manipulating IFC objects and corre-
460 sponding metadata. We have also developed a set of methods for enabling
461 the distributed manipulation of these IFC objects where various disciplines
462 associated with a project can work on the same IFC model. These APIs have
463 roles within the coordination system: (i) to support BIM process and multi-
464 cloud operability and (ii) to interface with the various applications that can
465 connect to the C4C framework. In our project partners have implemented a
466 Revit plug-in to connect Revit software (presented in Figure 6) to the C4C
467 framework and a filtering application which selects IFC objects based on pre-
468 defined suitability codes. The Revit plugin enables communication with the
469 cloud system by integrating the two main API calls (i) *getModel()* for facili-
470 tating model fetching from the cloud and (ii) *updateModel()* for submitting
471 model changes into the cloud.

472 The resulting functionality supports multi-cloud operation carried out
473 over an IFC model, by providing mechanisms to transfer data between dif-

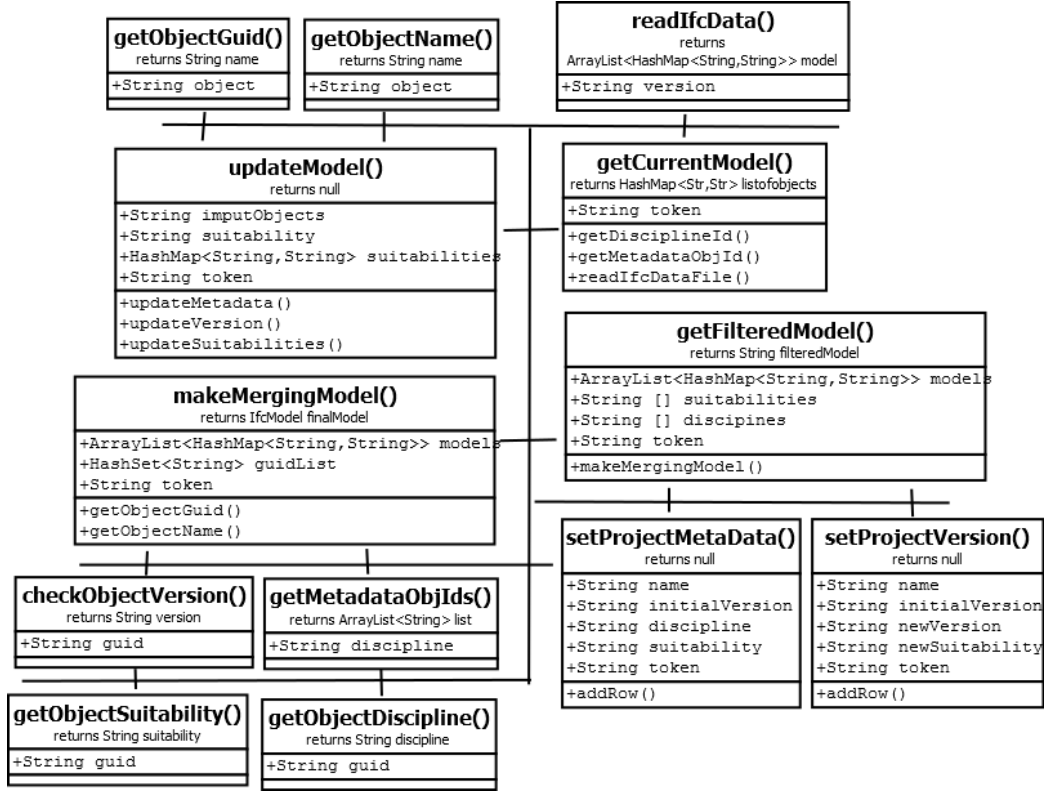


Figure 3: The C4C API

474 ferent disciplines. This allows disciplines to retrieve in real-time the latest
 475 version of an IFC object and to reconstruct the IFC model accordingly. Ta-
 476 ble 1 presents how the multi-cloud API can be used to enable collaboration
 477 between different partner sites.

478 We assume that each discipline has access to a cloud/data centre. The
 479 framework is initialized by calling “startC4CManager()” which then cre-
 480 ates the Masters and the Workers based on specific configuration files. If
 481 a site is not set to be a Master then the C4CManager will create a proxy
 482 in order to link with the existing data centre worker by calling “createIso-

METHOD	DESCRIPTION
addC4CBootStrapNodes()	Sets the bootstrap node
addPorts()	Adds ports for later configurations
bootstrapnodeIsUp()	Checks for any working bootstrapnode
createC4CMaster()	Creates a new master
createC4CWorker()	Creates a new worker
createC4CMasterGeneric()	Implements a generic master
findFreePort()	Looks for available free ports
isBootstrapNode()	Compares the current node with the bootstrapNode
sendMsg()	Sends a message to a destination IP on a specific port
sendMsgToAll()	Sends local subscription list to all nodes(not to bootstrapnodes)
startC4CManager()	Starts federation by creating a master and worker
startC4CWorker()	Starts a C4C local worker
startC4CMasterServer()	Starts a local C4C master
startC4CIsolatedWorker()	Starts a C4C isolated local worker
checkAvailableC4CWorker()	Checks for one available worker
checkAvailableC4CWorkers()	Checking for all available workers based on the number of tasks
getAvailableC4CWorker()	Checks for an idle worker
createTaskData()	Creates data associated with a task
getTaskInfo()	Retrieves task info. based on <i>taskID</i>
selectC4CWorkerCreateTask()	Selects a worker, then creates a task to insert to tuple space

Table 1: Multi-cloud API

latedWorker()” method. After the multi-cloud entities have been created, the C4CManager starts all the associated Masters and Workers by calling “startC4CMasterServer()” and “startC4CWorker()” respectively.

For our needs we have updated the tuple-space mechanisms and the format of tuples to comply with requirements related to data processing, data sharing and data storage as identified in the construction sector. Therefore, a tuple becomes an array formed of:

tuple-id: a unique identification of the tuple

491 **discipline-id:** unique identification of the discipline
492 **object-serialised:** a serialised version of the IFC model retrieved from discipline-
493 id
494 **event-id:** the type of operation; fetch or update

495 6. Evaluation

496 For testing our system we have conducted a trial using the data and
497 processes from a real construction project provided by the project partner
498 Costain identifying the Highways England construction of a new bridge on
499 the A556, as shown in Figure 4. To undertake the project trial we have
500 deployed our cloud coordination framework on a computing infrastructure
501 described in Section 4.3. The objective of this trial, as agreed with project
502 partners, is to demonstrate the benefits of collaboration in the construction of
503 A556 junction and to demonstrate that difficult linear infrastructure models
504 can be effectively managed by a Cloud/Hosted system to the benefit of all
505 parties.

506 6.1. Project trial

507 In the trial we have included different project disciplines and we have
508 provided access to the coordination system via a Revit plug in or a simplified
509 client that utilises the API described in Section 3.1 facilitating direct access
510 to IFC files. The disciplines involved in the project are listed below:

- 511 • Contractor - Costain.
- 512 • A cost consultant - Lee Wakemans Ltd.

513 • Designer - Capita.

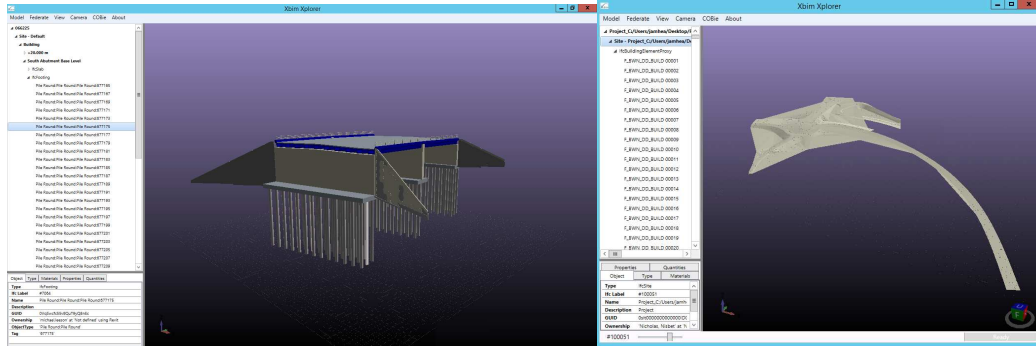
514 • Client - User.

515 The AEC project being considered is a bridge structure with auxiliaries,
516 which involves different disciplines contributing to various parts of the struc-
517 ture. We use four disciplines:(i) C-Contractor, (ii) Q-Cost Consultant, (iii)
518 E-Designer, (iv) O-Client. The IFC models sizes that we utilise in the demon-
519 stration are: 250MB, 145MB, 3.44MB, 48KB, all being parts of the bridge
520 on the A556 highway. These input models used for demonstrating the co-
521 ordination and the output model obtained after merging sub-models from
522 disciplines are presented in Figure 4.

523 In relation to the process explained in Section 6.2, the overall framework is
524 configured and disciplines are selected with individual roles; from a technical
525 perspective we consider that each server acts as a hosting environment for
526 a discipline and runs CometCloud (in a more general context, a discipline
527 can have multiple servers). The C4C framework is dynamically created at
528 runtime, enabling disciplines to join or leave at any given time. Based on
529 the use of CometCloud [9], each discipline has a master process that receives
530 task requests (IFC objects to update or retrieve) from other disciplines, and
531 is able to forward requests to other disciplines. Each discipline can also have
532 multiple worker processes that carry out actual task executions on locally
533 available resources.

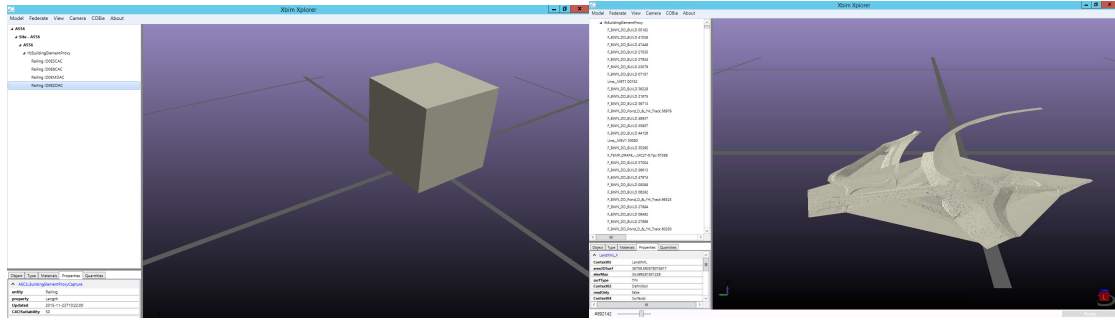
534 *6.2. Framework configuration and workflow*

535 The access to the C4C framework is ensured via a user interface devel-
536 oped based on technical and construction industry requirements. We have



(a) Input IFC Model: Size 3.44MB

(b) Input IFC Model: Size 256MB



(c) Input IFC Model: Size 48KB

(d) Output IFC Model: Size 366MB

Figure 4: Input and output models

537 developed the user interface for satisfying two functions: (i) initial set up of
 538 the C4C network and (ii) ongoing management of the system. The general
 539 sequence for the creation of a C4C network is presented bellow:

540 **Step 1:** Construction Industry Client [Client] decides to run the project in
 541 C4C framework

542 **Step 2:** Client downloads C4C software from the web address.

543 **Step 3:** Client installs C4C software, determining server IP address and
 544 opening the required ports.

545 **Step 4:** Client accesses C4C software via IP address and configures pri-

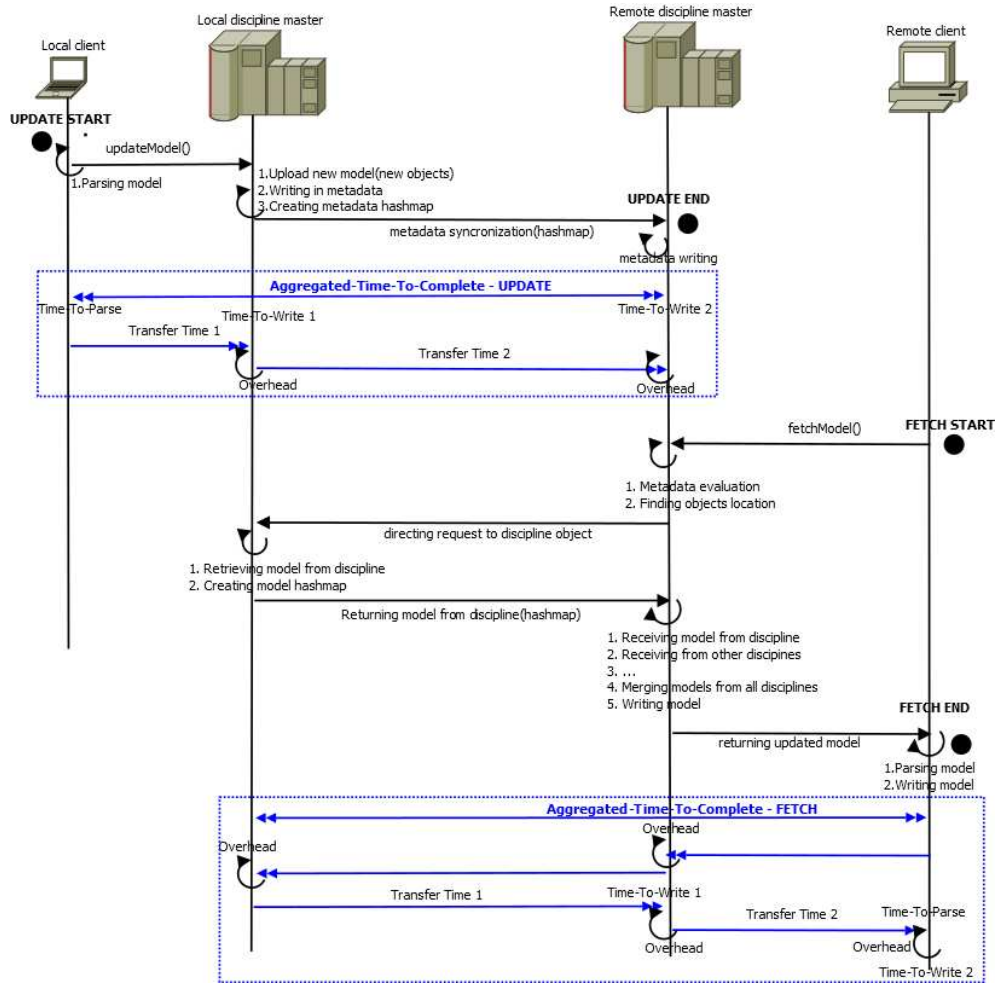


Figure 5: C4C workflow and process sequence

546 mary project information. Such information include: Project Name, Project
 547 Address, Client's Project Number/Reference, Client Company Name, Client
 548 Company C4C Primary Contact, Client C4C Primary Contact Email, Client's
 549 Nominated C4C Project Manager (not mandatory), Client's C4C Project
 550 Manager Email (not mandatory).

551 **Step 5:** Following the definition of the project information, the client (or

552 nominated C4C project manager) moves on to the first configuration table.
553 This defines the project disciplines (team members) and what information
554 each discipline can review. The client sends invitations to project disciplines
555 via email with a link to download the C4C software and the coordinator
556 server IP address embedded in the email.

557 **Step 6:** Disciplines receive email and install C4C software, noting the IP
558 address for accessing the coordination framework

559 **Step 7:** Disciplines access C4C software via IP address and configure their
560 discipline project information

561 **Step 9:** After establishing the C4C network, other ongoing management
562 such as adding, removing and editing disciplines and users can be achieved
563 through accessing the same 'core' configuration page. The workflow identi-
564 fying sequences within the C4C system is presented in Figure 5

565

566 *6.3. Trial and validation*

567 In this subsection we explain the entire scenario with participating disci-
568 plines and iterations that have been followed within the project trial.

569 **Prerequisites:** Four disciplines with associated users – each with an IFC
570 viewer, the C4C Client and a terminal displaying the appropriate C4C Master
571 Node to simulate different domains and network addresses. These disciplines
572 are project partners and are as follows:

- 573 • Discipline: C - Contractor: Costain- Connecting to master node 5.153.52.162
- 574 • Discipline: E - Designer: Capita - Connecting to master node 5.153.52.163

575 • Discipline: Q - Cost consultant - Lee Wakemans Ltd- Connecting to
576 master node 5.153.52.166

577 • Discipline: O - Client - Connecting to master node 5.153.52.164

578 **Step 1 - Discipline E: Starting the process** “Discipline E” creates an
579 initial bridge model and exports into .ifc using Data Design Systems (DDS)
580 viewer to show design, properties and ownership. Discipline E after creating
581 the model, uploads the model “A556-CAP-7000-S06-3D-S-1001.ifc” into the
582 C4C system with suitability S1.

583 **Step 2 - Discipline C: Another input from a different discipline.**
584 “Discipline C” is part of the project and receives the initial bridge design
585 proposal. Discipline C uses Design Builder viewer to colour and filter by
586 slope. After updates, discipline C uploads its model with suitability S0.

587 **Step 3 - Discipline E: Making changes and corrections, introducing**
588 **different suitabilities.** Disciplines E makes some model updates in Revit
589 (as illustrated in Figure 6), fixing railing and adding new IFC objects then
590 uploads the model with suitability S2.

591 **Step 4 - Discipline Q: Using the model to get non-graphic input**
592 **from a different discipline.** “Discipline Q”, using filtering (using the
593 API from Figure 3), downloads a costable bridge model, excludes suitability
594 S0, and S1, thereby excluding the ground works and the reinforcement, and
595 generates a cost report. Discipline Q uploads the model with suitability S4.

596 **Step 5 - Discipline O: Taking an overall view.** “Discipline O” fetches a
597 full, final integrated model with everything in it (as illustrated in Figure 7).
598 The model A556-CAP-7000-S06-3D-S-1001.ifc is viewed in Tekla BimSight
599 viewer to colour and filter by author and by suitability.

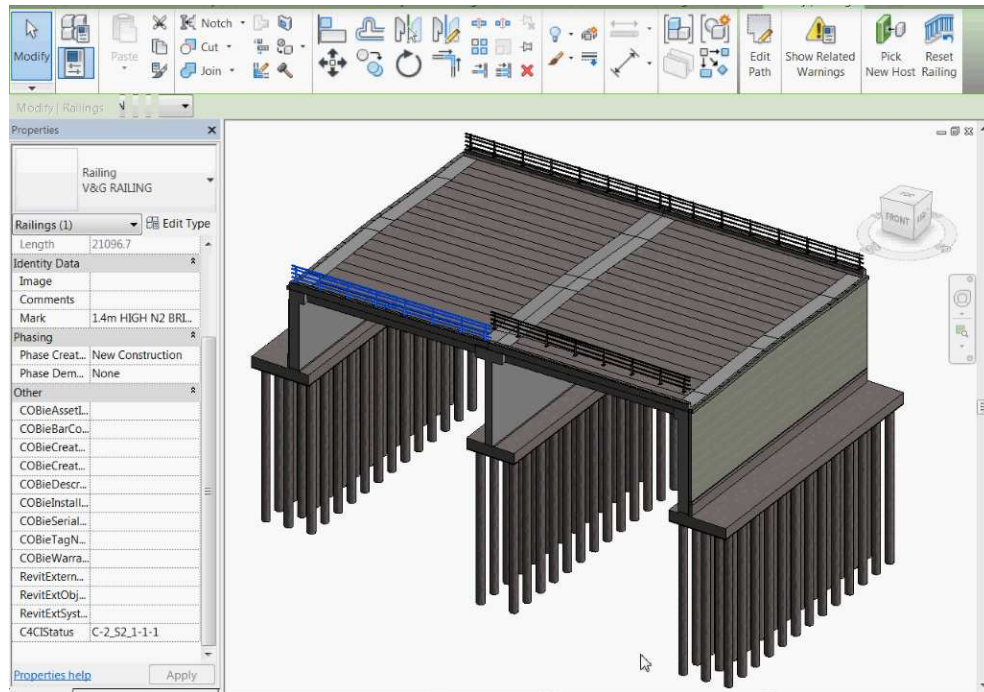


Figure 6: Revit plugin for C4C

6.4. Lessons learnt

This study is based on a collaborative cross-industry research project aiming to enable a collaboration environment for construction industry. The C4C project allows individual “nodes” containing the stored data to be “mapped” between the parties with a technology that can be deployed passively on each party’s computer systems. In essence, C4C allows a complete BIM dataset to be visualised, sourced from the information stored in the multiple locations, without changing how or where the original source material is kept, or who is responsible for that data. Bellow, we list several benefits that our framework provides in relation to multi-site construction project coordination.

Interoperability: The C4C system can support merging (not just federa-

```
5.153.52.162 - IBM1 - SSH Secure Shell
C:\Windows\system32\cmd.exe
[C4C-Notification] Need version:0
The current time is: 3:27:10.53
Enter the new time:
Fetching current version of model
Received IFC Data From C4C
Received IFC Data From Server
Received IFC Object: 4688631
Press any key to continue . . .

5.153.52.166 - IBM2 - SSH Secure Shell
Worker at //5.153.52.166:5571 workerid=1
StartWorker: main
recvTaskFromAppMasterPort: 15571
-> nodeURLList: [//5.153.52.163:5557]
OverlayControlInterface: network class is TCP
TCPSEVER EXECUTOR INIT SIZE 10
Join ID: 17588:16
Joining with bootstrap //5.153.52.163:5570
Initialized
Notifying predecessor with :17588:16 and //5.153.52.163:5557
To wait
Done waiting
Start the worker at //5.153.52.163:5557 workerid=1
StartWorker: main
recvTaskFromAppMasterPort: 15571
[C4C-Notification]Merging my model!
[C4C-Notification] Need version:0
[C4C-Notification] Merging model finalized!
[Notification-ComputeTask] Returning Model of Size:1812942
[C4C-Notification] Directly send back result to master: 2
[Notification-computeTask] Synchronization Complete!5:29:20

5.153.52.164 - IBM4 - SSH Secure Shell
taskid 3 is out
[Notification-createTaskData] fetch received
Application taskid 4 is out
[C4C-Notification]Merging my model!
[C4C-Notification] Received response from discipline Q Cost Consultant
[C4C-Notification] Fetch process finished!5:28:11
[Exception] No model on this discipline!
[C4C-Notification] Merging model finalized!
[Notification-ComputeTask] Returning Model of Size:0
[C4C-Notification] Directly send back result to master: 3
[Notification-computeTask] Synchronization Complete!5:28:10
[C4C-Notification] Received response from discipline O Client
[C4C-Notification] Fetch process finished!5:28:13
[C4C-Notification] Received response from discipline E Engineer
[C4C-Notification] Fetch process finished!5:28:35
[C4C-Notification] Received response from discipline C Contractor
[Notification-Receiver] Merging Models
[C4C-Notification] Fetch process finished!5:28:48
[Notification-Receiver] Model:0
[Notification-Receiver] Model:1
[Notification-Receiver] Model:2
[Notification-Socket] Created a combined model of 3 models
[Notification-Socket] Merging process finalized!
```

Figure 7: C4C output via terminal

tion) of various IFC models of an infrastructure project from multiple applications, clouds and/or actors (as demonstrated in Section 6), so as to be able to report from the resultant integrated model, using a secure and robust common interface. For example, the system can enable a “Constructor” to create an “integration project” in the cloud, and invite the client, the design team and his sub-contractors to join. Some sub-contractors may invite their own suppliers. All will grant the “Constructor” access to their various current cloud data services relating to the project.

Consistency: Our system can manage federated sub-models and integrate such sub-models into a single view. Based in this, a number of benefits can be observed related to: (i) detection of issues between models, such as dif-

622 ferences in volumes (clashes) and specification (properties) and groupings
623 (relationships) and (ii) the creation of a single model by eliminating discrep-
624 ancies and duplications found in the sub-models.

625 **Trust, Ownership, Flexibility:** In our framework each party stores their
626 data on, either their own business computer servers, or their choice of ex-
627 tranet and/or “Cloud” storage in accordance with their own business re-
628 quirements and protocols. This flexible approach facilitates the federation
629 of a data model in diverse locations and provides several advantages with
630 regards to the requirements that exist in a construction project:

- 631 1. Federation is a continuous process, not an event. It proceeds continu-
632 ously responding to the receipt of updates. At any time the complete
633 model is potentially available, but so too is the list of outstanding is-
634 sues.
- 635 2. Access is given to background information as is pertinent to the current
636 task by role, status and scope and pulled by the agent (who may further
637 restrict the view by role, status and scope).
- 638 3. Feedback to agents, whether human or automated, is via messages re-
639 questing clarification, analysis and correction. Examples include clashes,
640 evaluations, and discrepancies.

641 **IFC limitations:** Over the development of our project we have encoun-
642 tered several challenges with regards to the overall modeling process and to
643 efficaciously manage the Industry Foundation Classes (IFCs).

644 The most notable challenges of using this format is the issue of Globally
645 Unique Identifiers (GUIDs). GUIDs are used by the software to identify and
646 track objects being processed. In regards to IFC, GUIDs are used to track

647 objects from the BIM dataset and, through this, enable BIM software to know
648 the origin and revision history of each object within the model. Within the
649 IFCs, objects that possess a GUID are always a subclass of IfcRoot.

650 GUIDs become especially important in a federated model, where the data
651 may be spread across diverse locations and the presence of a GUID is key
652 to tracking the replication of each object. In its current iteration, the IFC
653 file format does not possess GUIDs for some data items (those that are not
654 subclasses of IfcRoot), an example of this is “IfcMaterial”. These objects are
655 generally seen as being a property of an object within a BIM model rather
656 than a stand alone object in their own right (even though in the IFC format
657 they are represented as objects). Thus, these types of objects are always
658 associated to an IFC object that does inherit from IfcRoot (thus possess a
659 GUID) and can be tracked within a model. Another problem that we faced
660 during development was the inconsistency of GUIDs from CAD packages,
661 as certain CAD packages change an object GUID during the import/export
662 process for IFC data.

663 In order to rectify these IFC limitations we have implemented a filtering
664 process which compares and thus removes all duplicated objects. This process
665 eliminates the problems related to (a) increased size of the model and (b)
666 duplication of data. The filtering process is performed both for objects that
667 possess a GUID (i.e. those that inherit from IfcRoot) and for those that
668 have no GUIDs. For objects inheriting from IfcRoot, this is performed by
669 doing a per object comparison between the updated IFC file and the model
670 stored on the server; any objects that have changed are updated along with
671 any inter-dependencies. For objects that do not inherit from IfcRoot, these

672 are managed by ensuring that any of these objects are always updated and
673 replaced when the IFC object (possessing a GUID) that they are associated
674 to, is updated.

675 **7. Conclusion**

676 This paper presents a cloud federated framework for supporting project
677 coordination and data sharing across multiple disciplines over the lifetime of
678 an AEC project. When companies collaborate on a particular project need
679 to share data efficiently – moving all data to a single server or location, with
680 subsequent access being controlled to various data sources at such a single
681 location.

682 We present a coordination model that facilitates companies to maintain
683 their own data (on a local server, within a private Cloud environment, or on
684 storage acquired from a public Cloud provider, such as Amazon), without a
685 need to migrate this data to a central site. We show how overlay-based Cloud
686 environment can be created, where all participants(institutions) in a project
687 can get access to a "logically" shared data/compute space. This is achieved
688 in this project by using the CometCloud system, which enables a number of
689 different sites to be federated using the concept of a "CometSpace" which
690 maintains physical instances of data at their original point of creation.

691 Access to data is facilitated through access rights mechanisms, a key
692 advantage provided by CometCloud that supports a secure and flexible en-
693 vironment for multi-site construction projects(unlike other Cloud systems
694 such as OpenStack). The key advantage of our cloud coordination frame-
695 work represents the near-instant sharing of data between authorised parties

696 in a development project, complete with quality assurance mechanisms and
697 the ability to track and see a history for the development of any object within
698 the dataset.

699 At a wider scale, we consider that our system can provide useful in-
700 sides into the process of large project coordination, proposing methods for
701 federating IFC models in distributed locations in a transparent and coher-
702 ent way. We also state that our cloud-for-coordination framework can map
703 into complex engineering workflows and can present applicability to other
704 domains such as building energy optimisation, water regulations or smart
705 energy grids.

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